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SOME ASPECTS OF FRICTION AND ANISOTROPIC RATIOS ON THE WORK HARDENING BEHAVIOR IN THE UPSETTING TESTS

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A B S T R A C T

Metal upsetting is a primary mechanical working operation to reduce the cross-section of the billets, and there are few challenges that are to be solved. When the billets undergo severe plastic deformation, the friction prevailing at the die/billet interface causes differential strain hardening and anisotropy in the metallic billets. The current work focuses on the effect of friction and anisotropy on the strain hardening behavior and hardness. AA2014 cast alloy were machined to an outer diameter of 24 mm, and an inner diameter of 12 mm with a thickness of 8 mm. Friction calibration curves were plotted from the ring compression test. Another set of solid cylindrical billets of the same composition with a height and diameter of 24 mm were compressed between the rigid dies. A distortion in the shape solid cylinders caused by friction, anisotropy, and their effect on strain hardening was studied after deformation. An equation was developed to predict he strain hardening behavior to investigate the effect anisotropy ratios on the strain hardening behavior. A novel approach to identify the effect of anisotropy ratios on the strain hardening behavior and hardness was proposed.

1. INTRODUCTION

AA2014 is a high-strength heat-treatable aluminum alloy primarily composed of aluminum (Al), copper (Cu), and small amounts of other elements. The alloy is known for its excellent strength-to-weight ratio , good machinability and for this reason , this alloy is widely used in automotive and aerospace industries. Bulk metal forming process, such as upsetting, aids in improving the strength and hardness of the material. Upsetting being the primary operation to reduce the cross-section of the billets draws the attention of researchers to work on the strain hardening behavior and friction. It is always challenging to improve the hardness of the material to a large extent with homogeneity. Because friction is one of the major process parameters that influence the upsetting process, a quantification technique by name Male and Cockroft calibration curves has been

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used over the decades to determine the magnitude of the friction at the die/billet interface. The studies of Male (1964) reported that the friction factor (m) could be determined based on the dimensional changes of the ring compressed between two sets of dies. Further studies on friction were carried out by Avitzur (1968), assuming that the billet will not barrel to plot friction calibration curves from a wide range of m =0 to m=1. The results reported by Avitzur were disproved by Sofuoglu et al. (2001) and suggested that as the deformation progresses, the magnitude of the friction factor will not be constant. The above studies reported so far could not differentiate good lubrication and poor lubrication based on dimensional changes of the ring. Robinson et al. (2004) concluded in their studies that expansion of the hole is an indication of good lubrication, and contraction of the hole is an indication of poor lubrication.

Strain hardening makes the metal stronger and harder, and the study of the strain hardening coefficient (k) is necessary to analyze the hardness of the billet after plastic deformation. Baskaran and Narayanasamy (2008) studied the work-hardening behavior of elliptical billets and concluded that the level of strain along the major and minor axes would influence the work-hardening behavior. The state of stress considered in the investigation also influences strain-hardening and the height to the diameter ratios of the billet. Al powder preforms with iron and aluminum oxide as reinforcements are made from a powder metallurgy route, and the powder preforms are compressed between the set of dies (Krishna et al., 2015, Inigoraj et al., 1998). The authors concluded that axial stress increases strain levels and reduces porosity. Recent studies reported that the combined effect of sintering temperature and lubrication greatly influences the work-hardening behavior (Ananthanarayanan et al., 2019).

Developing an equation by correlating the strain hardening coefficient (k) and strain hardening exponent (n) will be useful in conducting simulation studies and strain in homogeneity can be minimized (Sonmez & Demir, 2007). Similar kinds of studies were done by Narayanan et al. (2008) on annealed aluminum using finite element simulations. The equivalent strain obtained from the simulation was used to develop an equation for hardness measurement. The equation holds good when the material flows in the radial directions. Hari Krishna et al. (2017) and Seetharam et al. (2017) worked on the upsetting process of different alloys of aluminum. The authors conducted upsetting tests on Al-4%B4C preforms and observed a significant improvement in hardness when the billets were upset at a temperature of 400^0C and under hot forming and examined that there is an increase in the hardness of billets when operated at a strain rate of 0.1 S-1. Aging treatment can be best utilized for obtaining desired properties. AA2014 alloys were aged and upset to different strain levels, and a set of equations were developed constituting the equivalent strain and hardness .

To optimize the heterogeneous distribution of the hardness inside the billet, HariKrishna et al. (2015) optimized the process parameters and suggested that billets with lower height to the diameter ratio and low friction will reduce the heterogeneity of hardness distribution. Experimental studies related to the solid cylindrical upsetting tests and ring compression tests were carried out, and the authors analyzed the hardness distribution inside the billets by employing different lubricants. Hardness variations near the dead zone areas, bulge head, and at various places were well explained (HariKrishna et al., 2016a, HariKrishna et al., 2016b). Pöhlandt et al. (1998) and Pöhlandt et al. (2006) derived the anisotropy ratios and analyzed the formability of the formed billets produced from drawing and extrusion operation. Chirala et al. (2017) and HariKrishna et al. (2018) studied the above reports, and the effect of anisotropy on the formability of the billets and hardness in upsetting was investigated. After thoroughly investigating the literature, the authors attempted the effect of anisotropy on the strain hardening behavior, which is not available in the literature. Since friction also plays a role in the bulging of the cylinders, a correlation is required between friction and anisotropy.

Pöhlandt et al. (2006) categorized the anisotropy into tangential-axial anisotropy and axial-radial anisotropy, but the effect of these anisotropy ratios was not clearly distinguished anywhere in the bibliography. Fewer studies were report related to the effect of anisotropy assuming R_{rz}=R_{tz}, but no clear indication of the effect of R_{rz} and R_{tz} on hardness. The issues reported here motivated the authors to work on the effect of R_{rz} and R_{tz} on strain hardening and hardness distribution inside the billets.

2. MATERIALS AND METHODS

2.1 Ring compression test

AA2014 melt at a pouring temperature of 750^0C and flash of 3% and 6% was added to the matrix to make 3 sets of cast alloys. The fly ash mix was stirred at 700 rpm for better homogenization, and AA2014, AA2014+3% fly ash, and AA2014+6% fly ash solid rods of diameter 1 inch were obtained. The solid rods were turned to an outer diameter of 24 mm with a hole inside it of 12 mm and height of 8mm on the lathe machine. Thus, the samples are maintained at a size of 6:3:2 (Outer diameter: Inner diameter: height). To compare the friction variations, a ring compression test was carried out by employing soap, boric acid powder, and no lubricant in between H13 dies as illustrated in Figure. 1. Over the years green lubricants such as Boric acid and Soap have been used extensively as lubricant in the literature (Hari 2016c). These lubricants, such as boric acid, have excellent lubrication properties without requiring expensive disposal techniques (Erdemir 1991; Erdemir et al., 1991b).

The effectiveness of boric acid can be attributed to its low friction and shear strength values. Male (1964) developed a methodology to evaluate the friction prevailing at the die/billet interface. The friction factor is evaluated based on the dimensional changes of the ring compressed to different height reductions. The change in the hole diameter to the corresponding height reduction of the ring specimen is taken as a measurement.

AA2014 fly-ash

Figure 1. Ring compression test performed under different friction conditions

A curve is plotted by joining all the points of the diametral change at each and every instant of height reduction, as illustrated in Figure. 2. To evaluate friction between the workpiece and the dies, the ring compression was carried out at incremental level of 10% reduction in height. At each and every stage of the deformation, the reduction in the height and change in the inner diameter of the ring was noted down. The ratio of the strain due to the height reduction and change in the diameter gives the friction factor at any level of deformation. The average value of all the ratios gives the friction factor for the lubricant applied at the die/billet interface. The normal pressure applied at the each and every height reduction is listed in Table.1

Table 1. Normal pressure applied at each and every level of deformation

	Force applied (KN)		
% reduction in height	m=0.2	m=0.5	m=0.55
10	102	108	109
20	135	150	151
30	182	193	197
40	220	247	252
50	307	359	362
60	417	556	563

An indication of good lubrication and poor lubrication is was also explained by Robinson et al. (2004) based on the contraction and expansion of hole diameter which are examples of good and poor lubrication. When there is no lubrication, the slope of the curve corresponding to the lubricant applied is positive, and this tendency can be observed in Figure. 2. When a good lubricant such as soap is applied, the slope of the curve is negative.

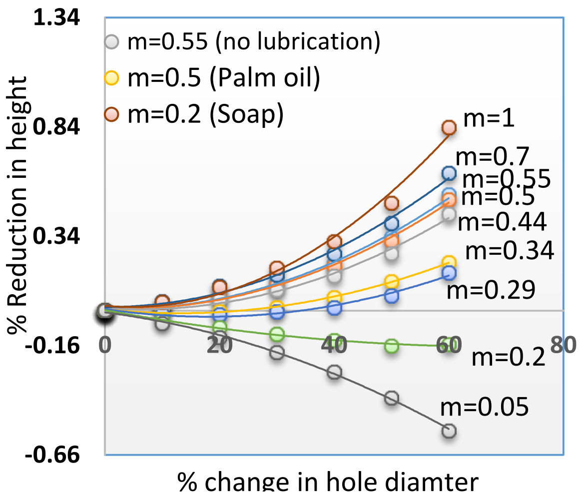


Figure 2. Male and Cockcroft calibration curves for different friction conditions

Three sets of billets, namely AA2014, AA2014+3% fly ash, and AA2014+6% fly ash was made out of the stir casting technique (HariKrishna & Davidson, 2019). As illustrated in Figure. 3a, the cylinders undergo some distortion on the shape, and this causes anisotropy. For a deformed cylinder, the strains after deformations are given by

$$\text{Axial strain } \varepsilon_z = ln\left(\frac{h}{h_o}\right) \quad (1)$$

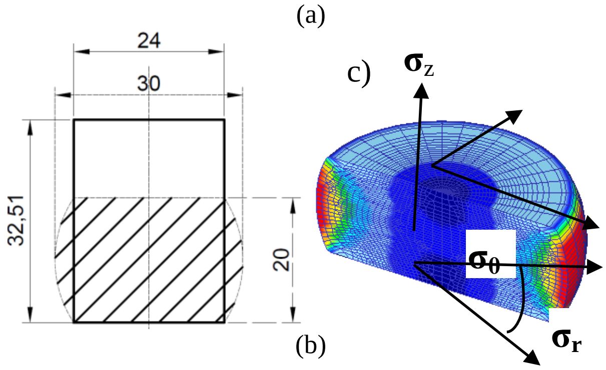
$$\text{Circumferential strain } \varepsilon_t = ln\left(\frac{w}{w_o}\right) \quad (2)$$

$$\text{Radial strain } \varepsilon_r = ln\left(\frac{r}{ro}\right) \quad (3)$$

$$\text{Tangential-axial anisotropy } R_{tz} = \frac{\epsilon_Z}{\epsilon_t} \quad (4)$$

$$\text{Radial-axial anisotropy } R_{rz} = \frac{\epsilon_Z}{\epsilon_r} \quad (5)$$

(a)



(b)

Figure 3. a. Upset billets (a) i. AA2014 ii. AA2014+3% fly ash iii. AA2014+6% fly ash. b) Geometry of the billet before and after deformation, and c) Upset billet representing anisotropy factor and stress planes

In the cylindrical upsetting test, the maximum principal stress (σ_1) is the circumferential stress, which is tensile in nature (σ_θ), and the minimum principal stress is (σ_2) the axial stress (σ_z). The parameters of anisotropy (R_0, R_{90}) are defined in 2 directions normal to each other. The anisotropy along the minor axis (R_0) is equal to tangential-axial anisotropy (R_{rz}), and the anisotropy along the major axis is the radial-axial anisotropy (R_{tz}). To analyze the effect of anisotropy on strain hardening, Hills quadratic yield equation known as the Hosford-Backofen equation was considered. This equation holds good for analyzing the anisotropy factors, and it is equivalent to flow stress (σ_o) (Hill, 1948).

$$\sigma_1^2 + \left(\frac{R_0(1+R_{90})}{R_0(1+R_{r0})}\right)\sigma_2^2 - \left(\frac{2R_0}{(1+R_{90})}\right)\sigma_1\sigma_2 \approx \sigma_o^2 \qquad (6)$$

Rewriting the equation (11) in terms of axial stress, hoop stress and antitropy ratios as equation (12).

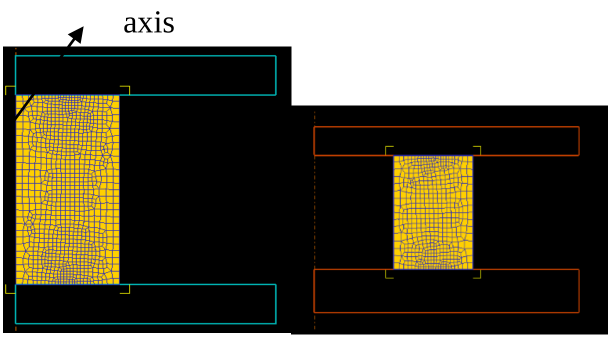
$$\sigma_1^2 + \left(\frac{R_{rz}(1+R_{tz})}{R_{tz}(1+R_{rz})}\right)\sigma_2^2 - \left(\frac{2R_{rz}}{(1+Rtz)}\right)\sigma_1\sigma_2 \approx \sigma_o^2 \qquad (7)$$

$$\sigma_z^2 + \left(\frac{R_{rz}(1+R_{tz})}{R_{tz}(1+R_{rz})}\right)\sigma_\theta^2 - \left(\frac{2R_{rz}}{(1+Rtz)}\right)\sigma_z\sigma_\theta \approx (K\varepsilon)^{2n} \qquad (8)$$

$$K=\left(\frac{1}{\varepsilon}\sqrt{\sigma_z^2 + \left(\frac{R_{rz}(1+R_{tz})}{R_{tz}(1+R_{rz})}\right)\sigma_\theta^2 - \left(\frac{2R_{rz}}{(1+Rtz)}\right)\sigma_z\sigma_\theta}\right)^n \qquad (9)$$

2.2 Simulation studies for Upsetting

To predict the effective strain in the radial direction, it is necessary to conduct finite element simulations. Axisymmetric configuration of the cylindrical upsetting tests and ring compressions test were carried out for predicting the strain contours. The whole configuration was modeled axisymmetric, as illustrated in Figure. 4. Billet material was assumed plastic, and the die was modeled as rigid. The levels of deformation were similar to the experimental investigations. Ludwik-Hollomom equation derived from the solid cylindrical upsetting was given as input to the finite element software (HariKrishna & Davidson, 2019).



(a) (b)

Figure 4. Axisymmetric modelling of (a) cylindrical upsetting and (b) ring compression test

$\sigma_o = K\varepsilon^n$

$= 154\varepsilon^{0.25}$	for AA2014 cast alloy	(10)
$= 248\varepsilon^{0.21}$	for AA2014+3% fly ash	(11)
$=379\varepsilon^{0.18}$	for AA2014+6% fly ash	(12)

The hollomon equation is given as input to the finite element software and the strain distribution inside the billet is measured as illustrated in Figure. 5. Strain is measured in the radial direction (points: P1, P2, P3……..) from the center of the specimen towards bulge head of the barreled cylinder. The intensity of strain is more at the center and decreases gradually on moving towards the bulge head because of differential strain hardening (Narayanan 2008). On the top of the billet and at the center, the strain will be zero because of the existence of dead zone region.

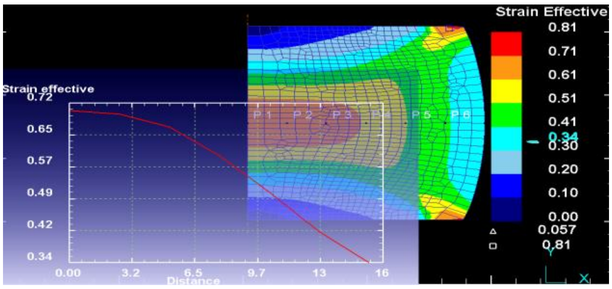


Figure 5. Strain Distribution at several zones inside the metallic axi symmetric cylinder

It can be observed that the R_{rz} was low initially and starts raising as the level of strain increases. In the case of R_{tz}, the anisotropy is high initially and decreases slowly as the strain level decreases. Both the anisotropy ratios are increasing after reaching a strain level of more than 0.4. At first, the radial strain increases because of the increase in the magnitude of the radial stress, which is very much smaller in magnitude compared to hoop stress. This radial stress promotes axial-radial anisotropy. Hoops stress promotes tensile strain in the circumferential direction, and this required a much higher load for deformation compared to radial strain. Due to this reason, the hoop strain is initially smaller compared to radial strain, and the magnitude of the R_{tz} is decreasing in magnitude compared to $R_{rz.}$ After reaching a threshold value of more than 0.4, the tensile nature of both the stresses (σ_r, σ_θ) promotes higher tensile strains along the major axis and minor axis, resulting in the increase of anisotropy ratios.

To predict the effect of anisotropy on strain hardening coefficient (K) with the increasing axial strain, a plot between K and ε_z was plotted (Figure 6 & Figure 7). The increasing axial strain increased both the radial-axial anisotropy and tangential-axial anisotropy. The increase in the R_{rz} coefficient decreased the magnitude of the strain hardening coefficient, and it is vice versa in the case of R_{tz}. This implies that an increase in the R_{rz} makes the stress required for deformation easy. The increase in the tangential-anisotropy caused by the hoop stress makes it hard to generate the required axial stress for deformation. The deformation becomes easier in the r-z plane compared to the t-z plane, and this is the reason for the variation in the strain hardening behaviour with the anisotropy ratios.

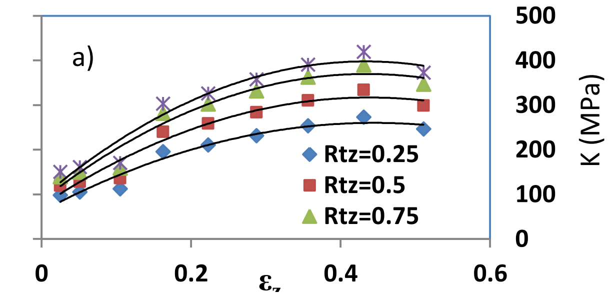


Figure 6. Effect of anisotropy on the strain hardening coefficient

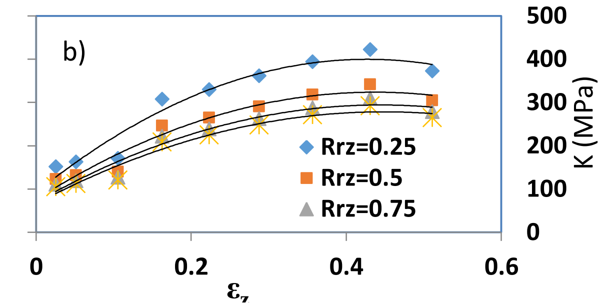


Figure 7. Effect of anisotropy on the strain hardening coefficient

5. CONCLUSIONS

The concept of the correlation between friction and anisotropy was well addressed. New lubricants that are environment friendly were used, and the friction factor corresponding to each lubricant was evaluated. The axial-tangential anisotropy has more effect on the strain hardening behavior compared to axial-radial anisotropy, and there is a threshold value of strain beyond which the R_{tz} is more predominant. The effect of anisotropy on the strain hardening coefficient was analyzed. Anisotropy in conjunction with the friction and level of deformation will have negative effect on the anisotropy.

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